National Aeronautics and Space Administration

SLS Block 1B Exploration Upper Stage
Low-G Slosh

Keith Clements
(EV41)
Steven Hough
(EV41/ESSCA/Axient/Dynamic Concepts)

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Contributions

- Contributors
  - Han Woong (Brian) Bae – (MSFC/EV41)
    - Machine Learning
  - Jacob Brodnick – (MSFC/ER42/ESSCA)
    - Fluid Dynamics and Co-Simulation
  - Tim Curry – (MSFC/EV42/ESSCA/Dynamic Concepts)
    - MAVERIC and Co-Simulation

Agenda

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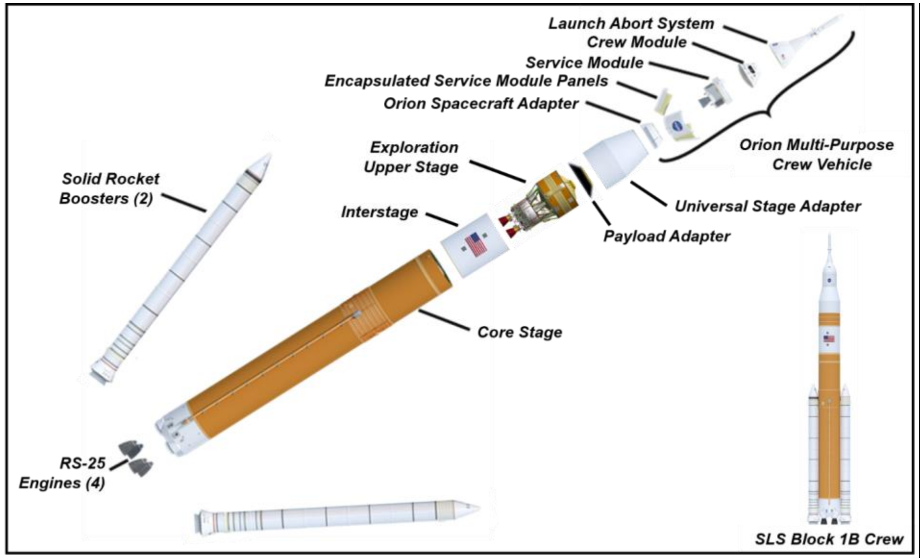
  - Motivation
  - SLS/EUS Vehicle (Block 1B)
  - Basics of Artemis IV mission
  - Coast slosh analysis performed to date
    - Analytical low g slosh modeling based on Dodge
    - Low-g comparison to “High”-g
    - High-g slosh applied to low-g in Monte Carlo
    - Direct application of CFD slosh forces and moments in MAVERIC
  - Coast slosh analysis in progress
    - MAVERIC + CFD Co-Simulation
    - Machine Learning Model

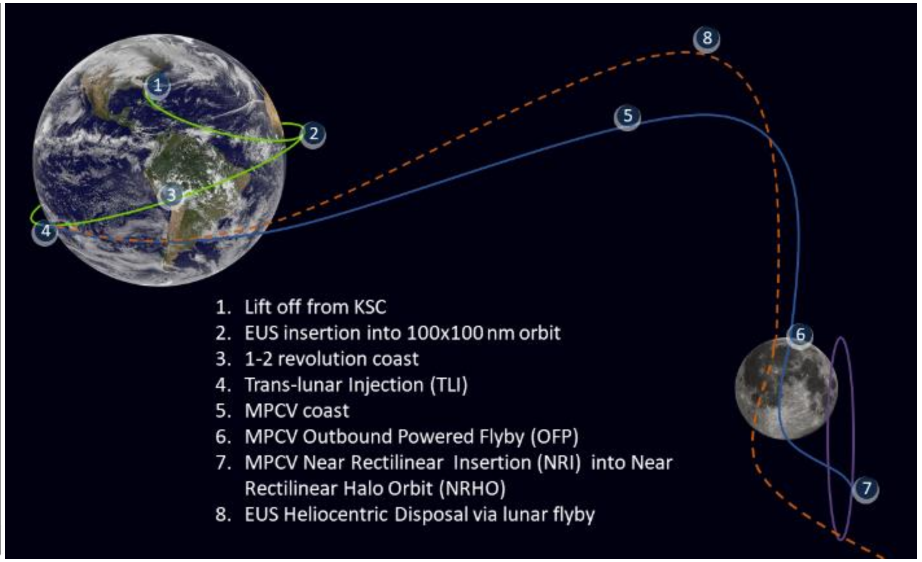
Motivation

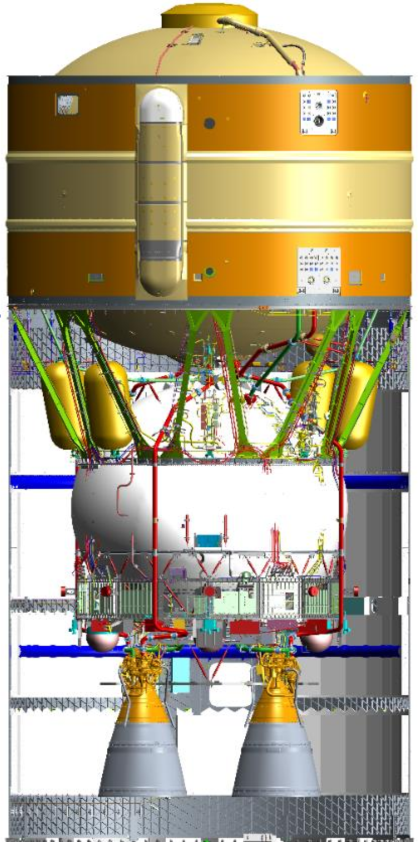
- Low-G Slosh RID (Review Item Discrepancy) from Block1B CDR
  - When the fluid moves about the EUS tanks during coast flight (zero and low g), forces and moments are imparted on the vehicle.
  - These forces and moment act as disturbances to the EUS control system and can induce additional thruster firings and hydrazine usage
  - The EUS hydrazine budget carries an allocation for low-g slosh induced usage
  - This forward work and RID Corrective Action Plan will seek to demonstrate that sufficient hydrazine margin is being carried for the low-g slosh induced usage
    - Slosh dynamics are being quantified using Computational Fluid Dynamics (CFD) with a volume of fluid (VoF) method of distinctly representing liquid and vapor.
    - Bounding trajectories are being used as input to CFD for quantification of open-loop slosh dynamics which will then be fed into MAVERIC.
    - Co-simulation of CFD and MAVERIC will be conducted for simulation of closed-loop slosh dynamics.
    - Closed-loop slosh modeling will be done to quantify uncertainty in open-loop slosh modeling through duplication of dynamics from a single trajectory.

GR&A

- Artemis IV (Crew) Mission Profile:
  - SLS CS and first burn (ascent burn) of EUS used to insert EUS + USA + CPL + MPCV stack into a 100 nmi circular orbit while meeting core disposal constraints.
  - EUS + USA + CPL + MPCV remain in LEO parking orbit for ~1-2 orbits for checkout prior to the TLI burn (EUS 2nd burn).
  - Following TLI, blowdown remaining EUS propellant and perform RPOD activities with Orion







Pertinent Vehicle Activities

- LEO Coast:
  - EUS Ascent burn concludes with a 2-2 staggered engine shutdown
    - Load constraint
    - Staggered shutdown does contribute to slosh excitation
  - Excerpt of attitude timeline….

Liftoff, first vertical motion & KSC/JSC mission handover (T1 event)
SRB separation for both boosters: STAGE3 cmd (T3 event)
Core Stage MECO command (T4 event)
EUS/Core Stage Separation Initiated (T5 event)
EUS initiates Ascent burn (T6 event)
EUS starts rotation to Sun Normal attitude
EUS begins 180 deg thermal roll
EUS begins 180 deg thermal roll
EUS begins 180 deg thermal roll
EUS begins 180 deg thermal roll
EUS starts roll portion of rotation to TLI burn attitude
EUS starts pitch/yaw portion of rotation to TLI burn attitude
EUS initiates Trans-Lunar Injection burn (T8 event)
EUS starts rotation to blowdown attitude
EUS starts transverse spin
Propellant blowdown begins

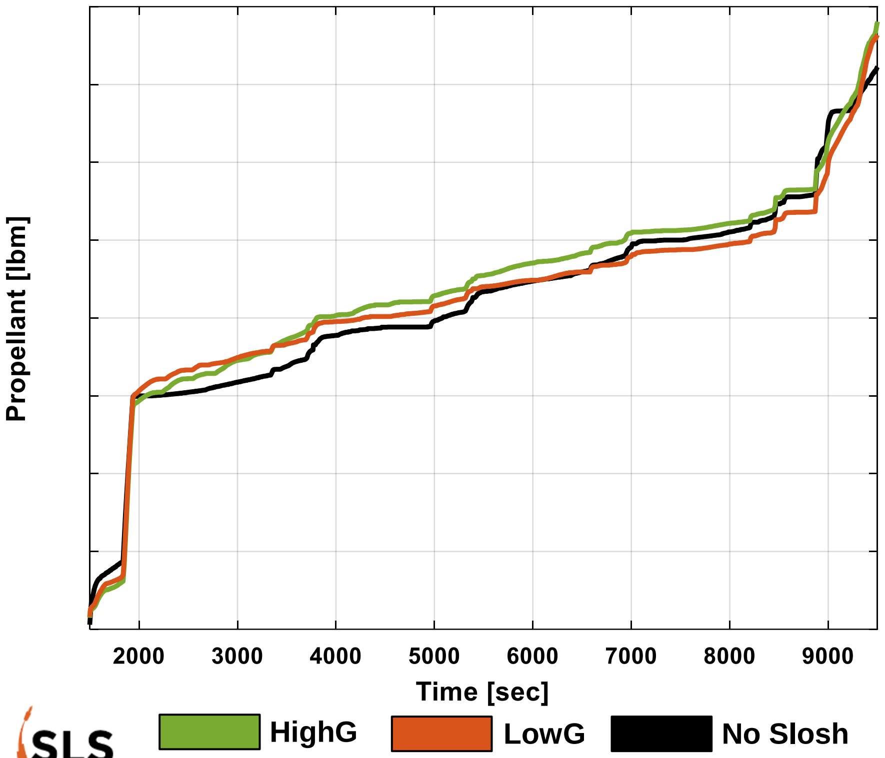
  - Throughout coast flight, propellant management is key concern (must keep liquid propellant away from vent ports at top of tank)
    - Addressed via axial RCS settling firings, LH2 Continuous Vent System, and additional fill level baffle

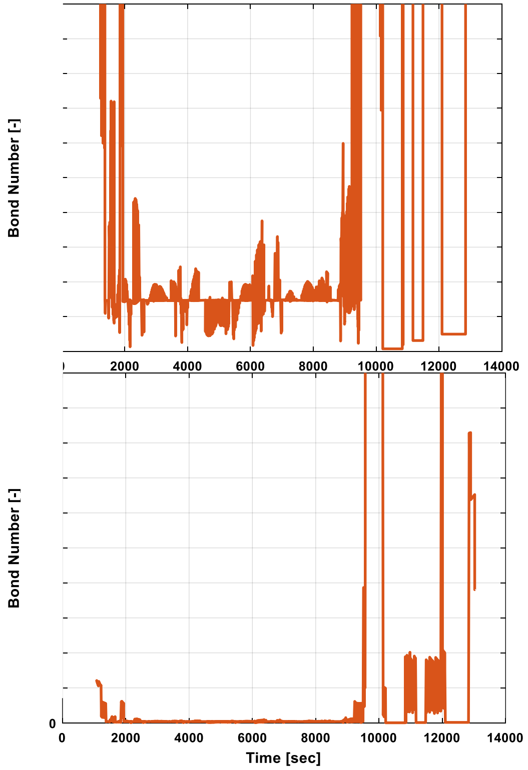
Low-G slosh model

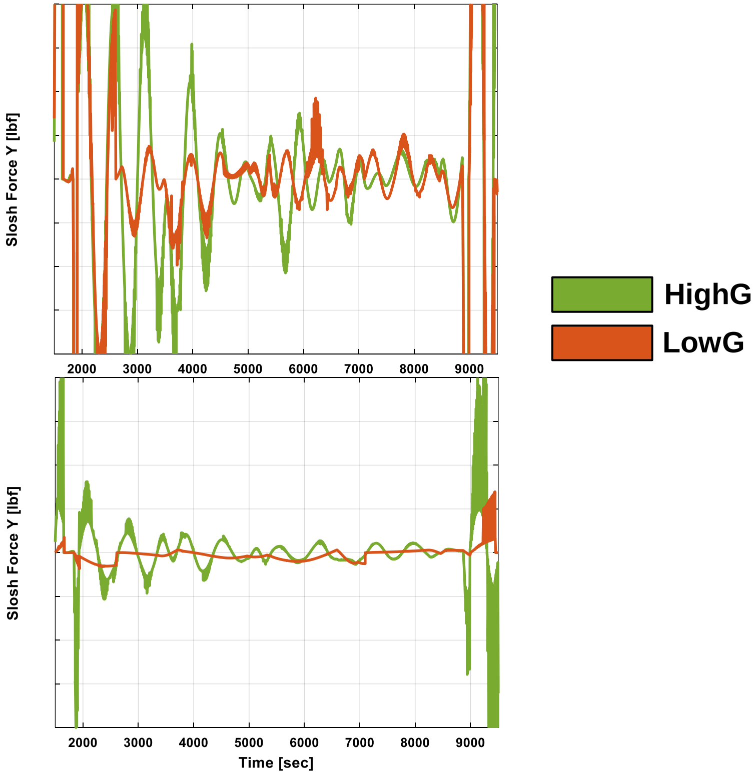
- Low-G slosh model development [*Alaniz, 2012*]
  - A low-g slosh model with surface tension effects was derived based on Dodge's early work [*Dodge & Garza "Experimental and Theoretical Studies of Liquid Sloshing at Simulated Low Gravity(ies)", 1966 and 1967*]
    - The results from the derived low-g slosh model are similar to Dodge's work for Bond number >30 [*Dodge, "The new "Dynamic Behavior of Liquids in Moving Containers"", 2000*]
    - The derived low-g model can be used for Bond number > 10
  - For 10 < Nbo < 200,
    - slosh frequency from low-g model is similar to high-g model
    - slosh mass from low-g model is about 7% less than those from high-g model
    - damping ratio relationship to high-g model, a function of tank geometry
  - The derived low-g model can be used for Nbo > 10
    - When Nbo <10, a reliable low-g model has not been found
  - Limited by induced accelerations (RCS firings or maneuvers) that can break free surface
    - Good model for steady state/settled results. Analytical model most likely not valid in highly dynamic environment like SECO1

Low-G slosh model compared to High-G model

- Low-G slosh model tested in MAVERIC for EUS Coast and compared to High G Model
  - Overall impact on hydrazine was small and inconclusive
  - Slosh forces for LO2 tank are similar between high and low g model
    - Differences observed for LH2. However forces are less.
  - Additional testing showed hydrazine impact very similar when using high g or low g slosh

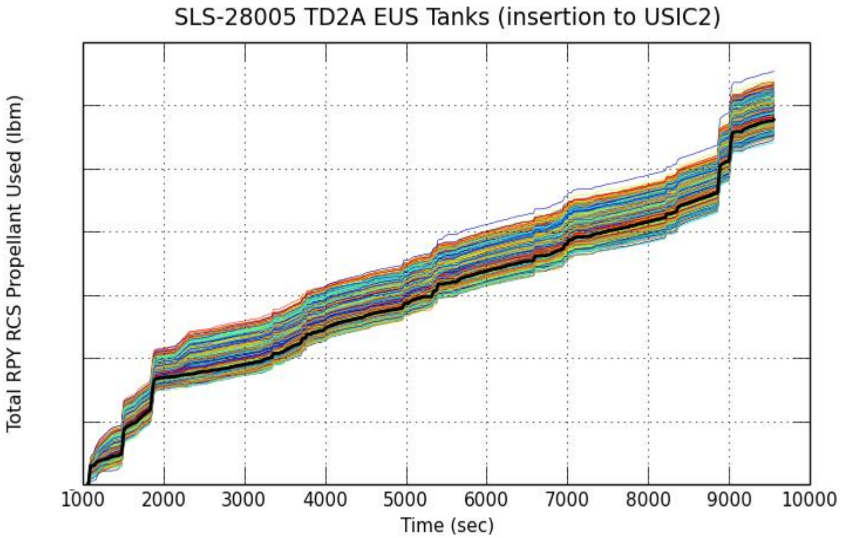


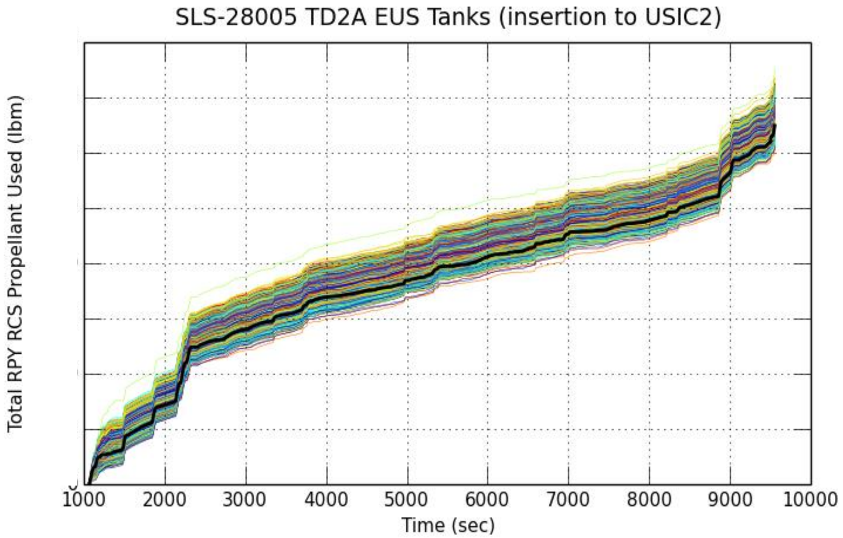




Low-G/High-G slosh modelling in MAVERIC MC

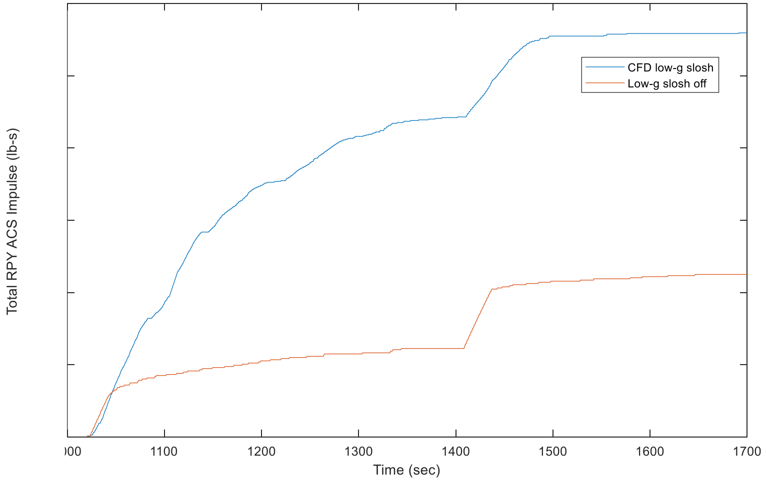
- High-G model application to low-g (with MAVERIC constraints)
  - As similar hydrazine usage was observed between standard slosh model and low-g slosh model, ran a MAVERIC Monte Carlo with standard slosh model enabled throughout flight
    - Reduced low accel limit and held frequency below 0.00005 g's
    - Limited slosh displacement to the tank radius
  - With applied model augmentations observed **moderate** impact to hydrazine due to slosh

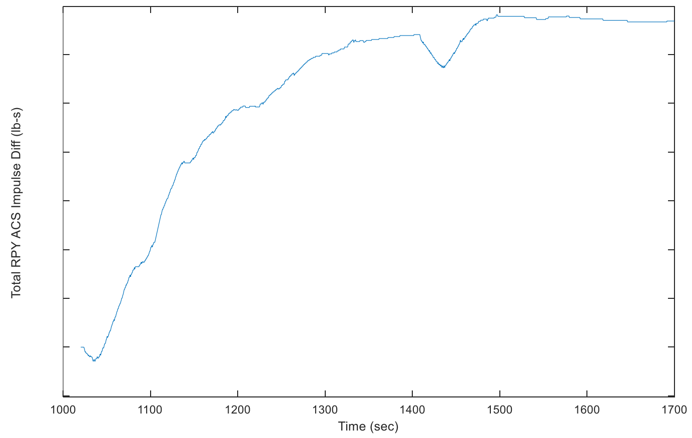




CFD Forces/Moments

- Slosh CFD Force/Moment applied to MAVERIC dispersed seed
  - Boeing provided CFD output data for a single MAVERIC seed (DAC2R seed 680) for ~600 sec
    - MET 950 to 1550 sec (SECO1 @ ~1000 sec)
    - LH2 and LO2 provided
  - These forces and moments were applied in MAVERIC as a disturbance on the vehicle using the same configuration/seed as was used as input to the CFD
    - Observed moderate impact to hydrazine over 550 sec period



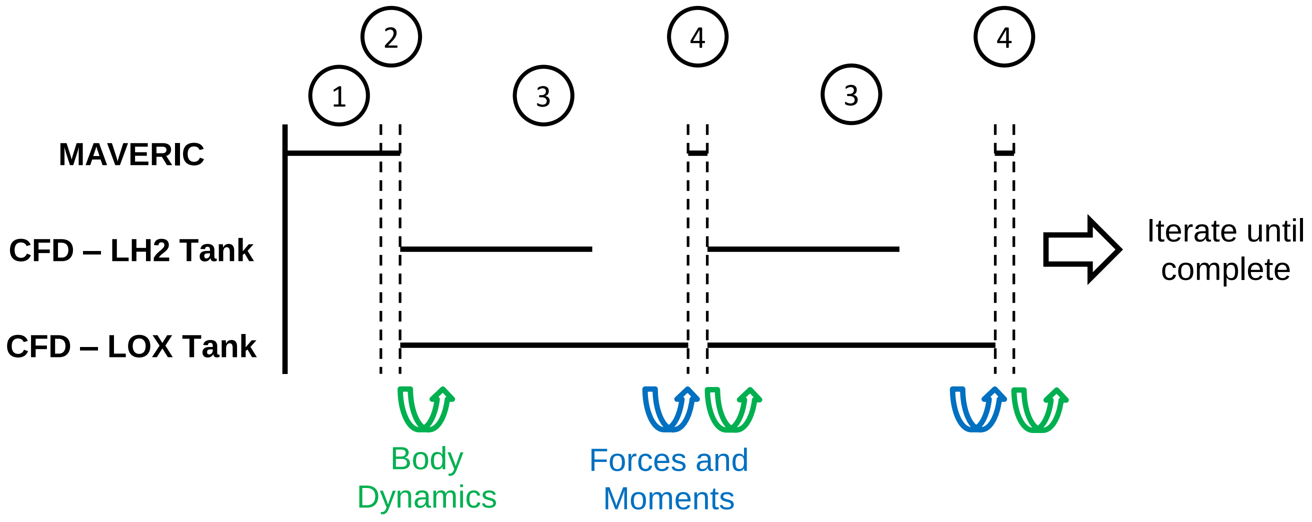


  - Boeing subsequently provided an additional CFD data set for the same MAVERIC seed that included modeling corrections and included data for 2500 sec of LEO coast rather than just 550 sec
    - When incorporated into MAVERIC, observed significantly less hydrazine impact and all hydrazine impacts are observed in first 400 sec following SECO1(open work)

MAVERIC + CFD Co-Simulation

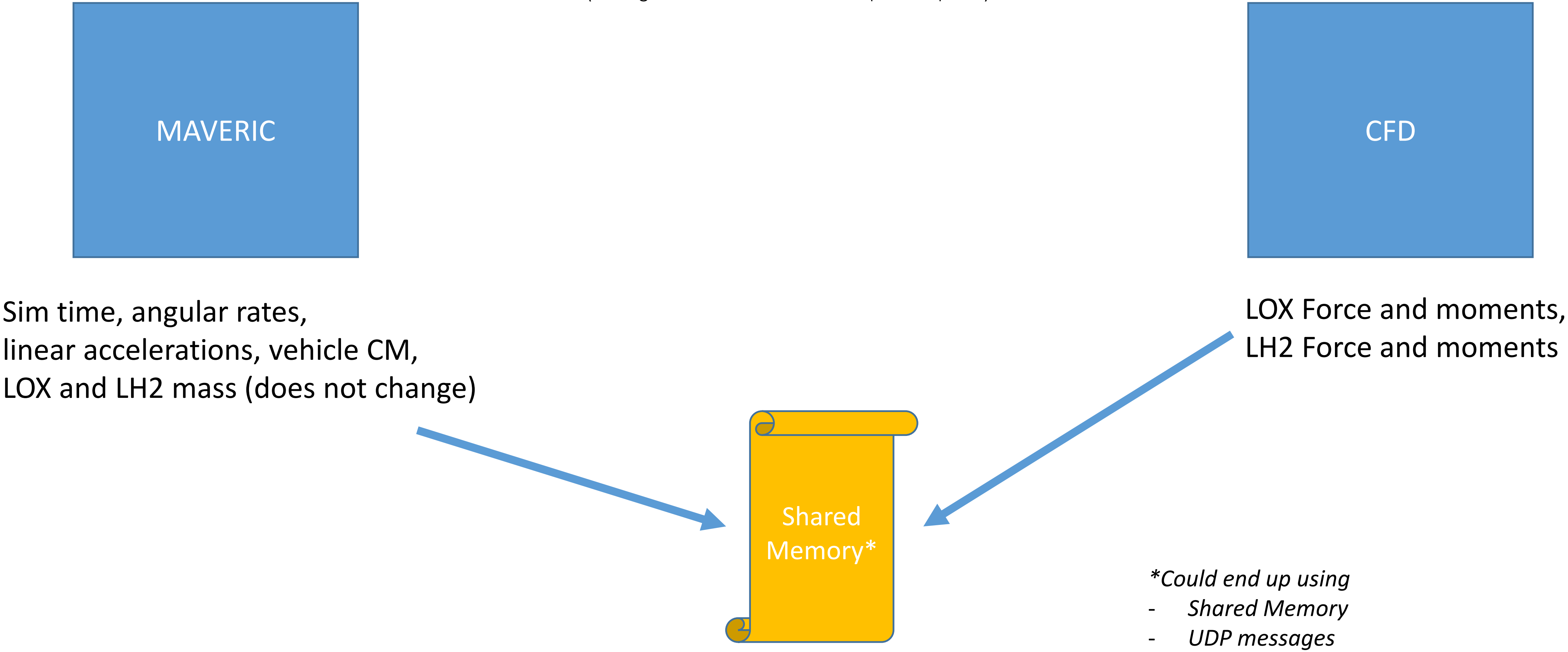
- Simulation of vehicle dynamics with closed-loop sloshing allows slosh to respond to the controller and develop differently than it would in open-loop modeling where slosh motion responds to a predetermined trajectory.
- A hand-off procedure is used to for modeling of closed-loop slosh dynamics.
  1. MAVERIC simulates using established high gravity sub-models of propellant slosh until EUS engine shutdown.
  2. MAVERIC simulates 1 time step using high gravity sub-models of propellant slosh.
  3. CFD simulates until reaching the current MAVERIC time interpolating MAVERIC provided body dynamics as it progresses.
  4. MAVERIC simulates 1 time step using CFD generated net forces and moments on each EUS tank.
  – Steps 3 and 4 are repeated until the desired end time is reached.
- Open-loop and closed loop simulation results will be compared with regards to RCS mass usage to quantify the uncertainty related to slosh feedback.

Illustration of the Co-simulation Process



Pictorial Diagram

(Configuration on HECC Ames Supercomputer)



Synchronize through shared wait flag

**Could end up using*

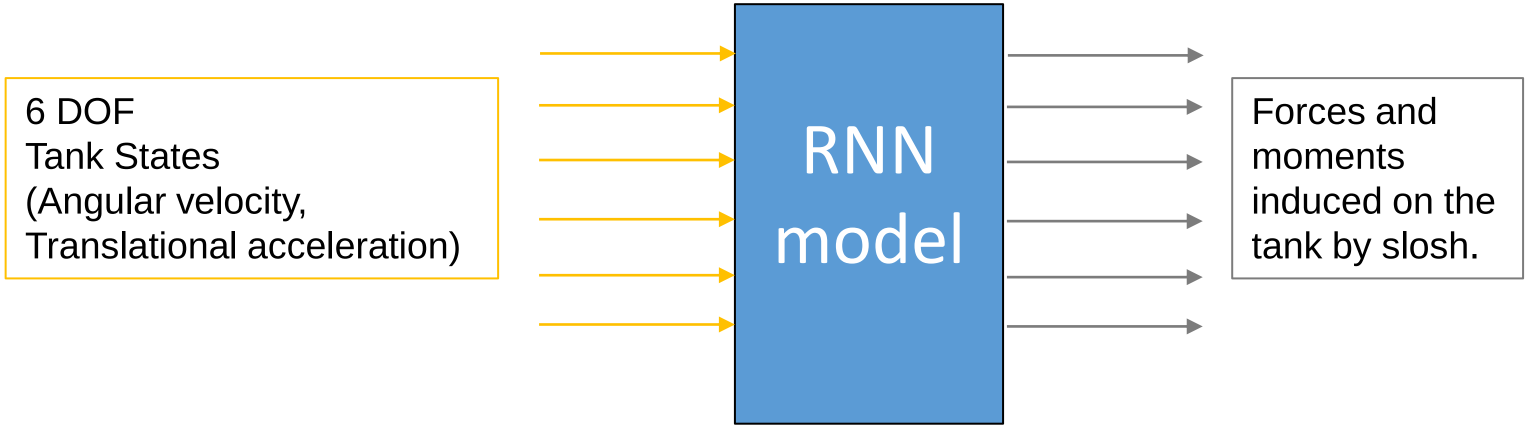
- *Shared Memory*
- *UDP messages*
- *Setting file over NFS (network file system)*

MAVERIC + CFD Co-Simulation

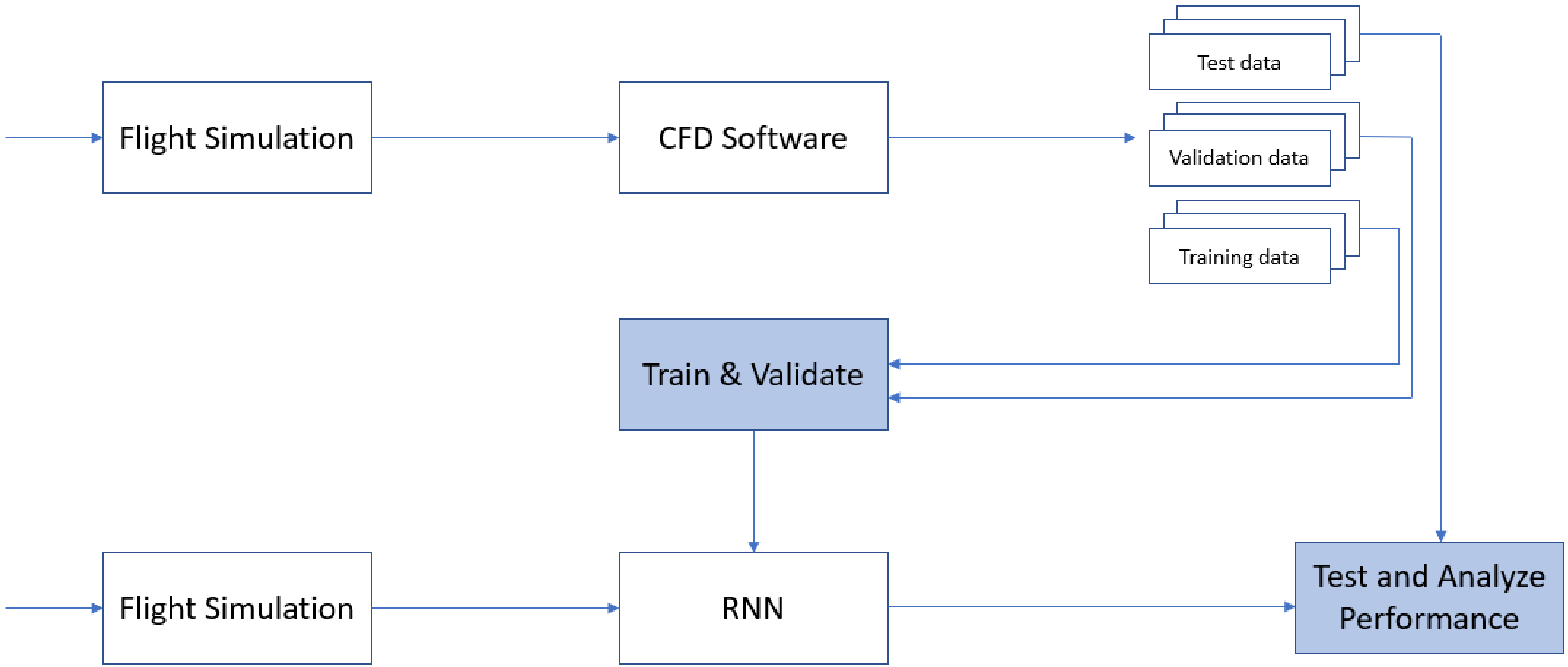
- Implementation Details
  - Proper handling of mass properties
    - Since CFD is providing all fluid induced forces and moments to MAVERIC, the MAVERIC propellant mass must be removed from vehicle equations of motion
  - Due to long CFD run times, need a plan of action for restarting after possible simulation crash
    - Logging data every time of interface to create a time series file.
      - Then to restart, MAVERIC could read to end of file then continue.
  - Apples-to-apples simulations required when performing open loop to closed loop sensitivity

Low G Slosh Machine Learning Approach

- Objective
  - Utilize a machine learning model that closely tracks computational fluid dynamics (CFD) models, which can capture the highly dynamic main engine cutoff event and the several hundred seconds that follow the engine cutoff, where slosh dynamics have the largest impact on the control system and require the most hydrazine usage to counteract.
- Approach
  - The proposed approach is to utilize Recurrent Neural Network (RNN) to accurately train and predict the complex and dynamic CFD slosh forces and moments in tanks with six degrees of freedom (6-dof) states, including angular velocity and translational acceleration.

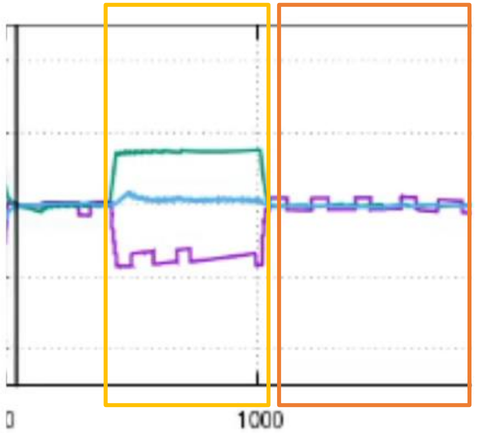


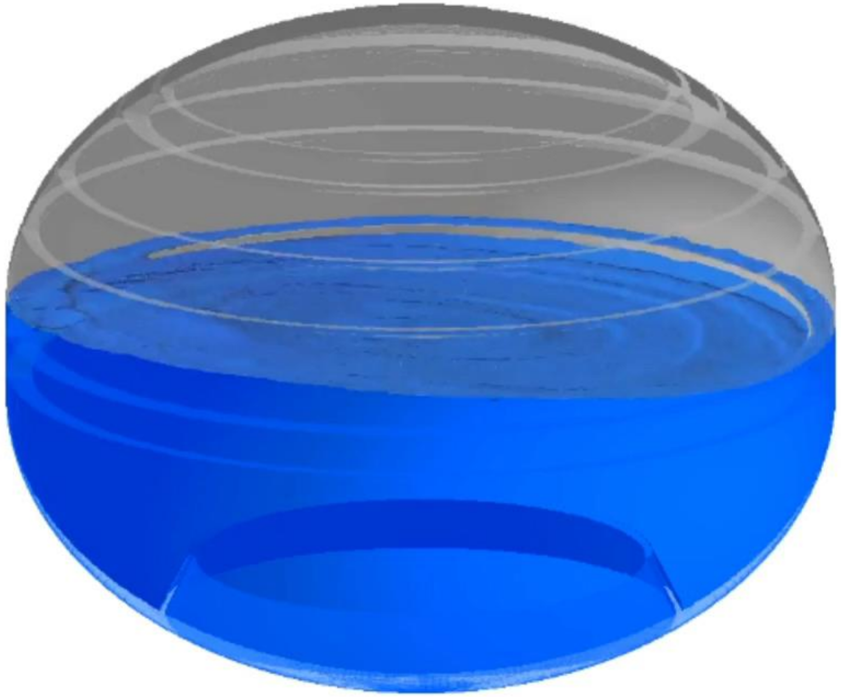
Overall CFD + Flight Simulation + ML Workflow

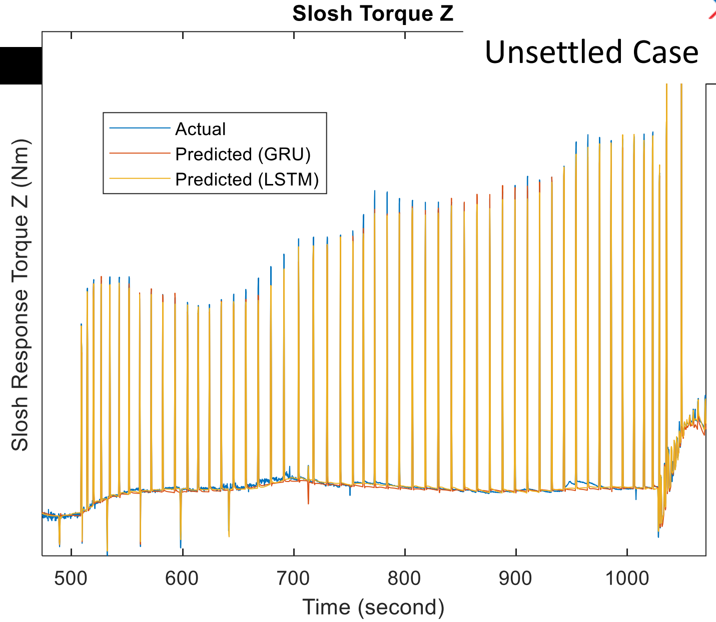


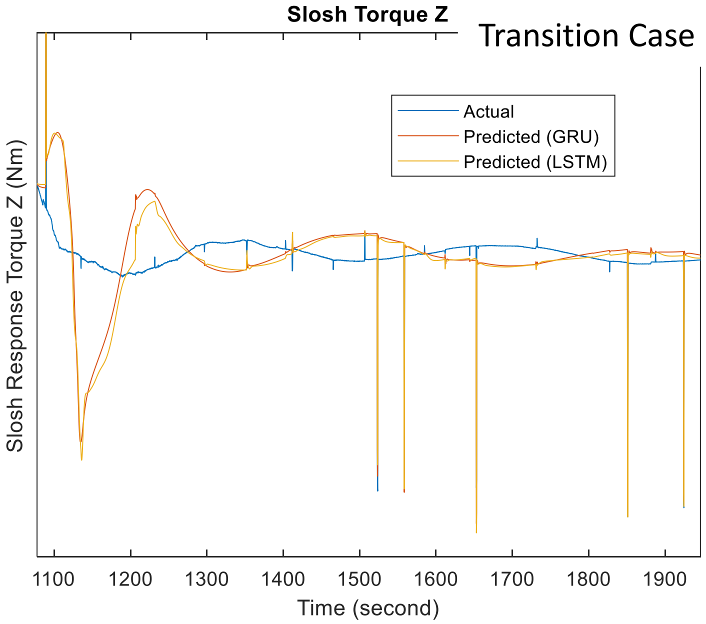
Demonstrations

- RNN's predicts dynamics in unsettled case (yellow box) very well, while not so well with the transition (red box) to the settling case where the propellant is heavily perturbed.









Low G Slosh Machine Learning Approach

- Ongoing/Future Work
  - Deploy the RNN models on high-fidelity simulations for closed-loop dynamics.
  - Generate additional CFD data to enhance our modeling capabilities for EUS low-g slosh dynamics.
    - This will enable us to more accurately predict and mitigate any potential issues related to these dynamics.

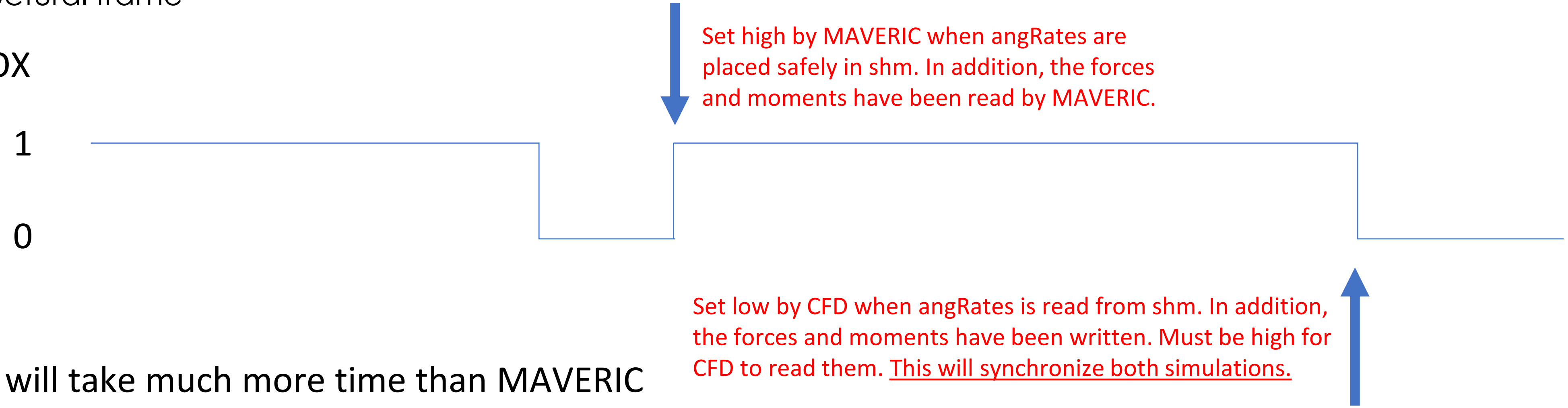
Backup

- Backup

MAVERIC + CFD Co-Simulation

- Shared Memory Segment
  - Current MET time in seconds defined by MAVERIC
  - Wait Flag:
    - CFD app controls this flag to allow MAVERIC to continue.
    - MAVERIC waits for the falling edge of this flag to continue.
  - CFD Output:
    - LOX Tank Force and Moment vectors from CFD in EUS body coordinate system.
      - Force (in lbf) and Moments (ft-lbf)
    - LH2 Tank Force and Moment vectors from CFD in EUS body coordinate system.
      - Force (in lbf) and Moments (ft-lbf)
  - MAVERIC Output
    - Angular Rates (rad/sec) from MAVERIC applied at the EUS vehicle cg.
    - Vehicle's Linear Accel (ft/sec2) which includes Gravity (ft/sec2). In body frame
    - Vehicle CM in Structural frame

MAVERIC_finished_LOX



* CFD will take much more time than MAVERIC